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CROSS SECTIONS FOR FORWARD-ANGLE ELASTIC SCATTERING OF 7 TO 10 MeV NEUTRONS FROM CARBON, NITROGEN, AND OXYGEN

by

William P. Bucher
Clinton E. Hollandsworth
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James E. Youngblood

June 1973

USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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REPORT NO. 1652

WPBucher/CEHollandsworth/
ANiiler/DMcNatt/JEYoungblood/rr
Aberdeen Proving Ground, Md.
June 1973

CROSS SECTIONS FOR FORWARD-ANGLE ELASTIC SCATTERING OF 7 TO 10 MeV NEUTRONS FROM CARBON, NITROGEN, AND OXYGEN

ABSTRACT

Absolute differential cross sections for the elastic scattering of 7.40, 7.55, 8.00, 8.55, 9.00, and 9.50 MeV neutrons from carbon, nitrogen, and oxygen in the angular range from 2.5° to 15° have been determined. Measurements were made relative to the scattering from lead by use of a special-purpose collimator. The cross section scale was then established by absolute measurements for lead in a ring geometry experiment. The results for nitrogen are consistent with recent measurements at other laboratories which suggest that the discrepancy in previous nitrogen cross section data around 7-8 MeV neutron energy arose from an underestimate of the elastic scattering cross section. The data presented in this report represent the first direct measurements of neutron scattering cross sections for light elements at very small scattering angles.

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I. INTRODUCTION

A technique, which utilizes a neutron collimator assembly designed to provide shielding along the entire path length of scattered neutrons from scatterer to detector, has been developed for measurements of the forward-angle elastic scattering of fast neutrons.

In a previous report[1*] we described the experimental method and presented results for scattering of 7.55 and 9.50 MeV neutrons from carbon, nitrogen, and oxygen. These experiments were motivated by the desire to provide experimental data bearing on the resolution of an existing discrepancy[2] in the nitrogen cross sections in the 7 to 10 MeV range of neutron energies. The results of air transport calculations[3] for neutrons are sensitive to errors in the input cross sections of the magnitude and nature of those implied by the discrepancy. Our results[1] for N at 7.55 MeV indicated that the 0° cross section was approximately 40% higher than the minimum value given by the Wick limit and implied that previous measurements of the elastic scattering probably yielded an underestimate of the total cross section for elastic scattering.

The new measurements reported here were initiated primarily to provide additional data concerning the discrepancy. Since initiating the present work, new measurements at large angles ($15^\circ \leq \theta \leq 160^\circ$) between 7 and 10 MeV neutron energy have been reported.[4,5] The results of these recent measurements are consistent with our results and produce integrated elastic cross sections approximately 20% higher than the earlier elastic scattering data[6] in the 7 to 9 MeV range of neutron energies.

II. EXPERIMENTAL PROCEDURE

The measurements were carried out at the BRL tandem Van de Graaff facility. Deuterons from a direct-extraction diode source were pulsed at a repetition rate of 2 MHz and klystron bunched. The overall time resolution for the detection of elastically scattered neutrons was approximately two nanoseconds. After acceleration, the pulsed deuteron beam was used to produce neutrons through the $D(d,n)^3He$ reaction in a D_2 gas cell with a thin (3.5 or 5μ) Mo entrance window. The cell length was varied from 2 cm to 3.8 cm during the course of these measurements. Neutron production was monitored by observation of the neutron time-of-flight spectrum in a scintillation detector positioned approximately 1.5 meters from the source.

The experimental arrangement is shown in Figure 1. A scattering run with the sample in the scattering position (see Figure 1) is followed by a background run, for the same number of monitor counts, with the sample in the attenuating position. The scattering samples are in the form of discs 26 cm in diameter. The liquid samples, N_2H_4 and H_2O are confined

* *References are listed on page 22.*

in thin-walled stainless steel containers. Scattered neutrons are detected in NE-213 scintillators. Standard neutron time-of-flight techniques, including neutron-gamma ray discrimination, are used for background suppression. A general description of the experimental techniques has been given in a previous report.[1]

All scattering measurements with the collimator of Figure 1 are made relative to the scattering from lead. The absolute cross sections for lead are then determined by ring geometry measurements.[7] This approach is particularly feasible due to the high scattering cross section for lead, approximately 7 barns/sr. at 3°, a factor of ten or more higher than those of carbon, nitrogen, or oxygen. The excellent counting statistics of the lead data taken with the collimator introduce only a small uncertainty in the final data.

In the ring geometry measurements, the signal to background is sufficiently high to allow good counting statistics. However, it is necessary to correct these data for systematic errors due to air scattering by performing similar measurements with polyethylene (CH_2) rings. The final data for lead are also corrected for multiple scattering and, to the second order, for the finite sizes of the source, scatterer, and detector. The angles for which measurements were made correspond closely to those measured with the collimator so that errors due to either interpolation or extrapolation are small.

The lead data at five energies (7.55, 8.00, 8.55, 9.00, and 9.50 MeV) were compared with the predictions of the Perey-Buck optical model[8] using the equivalent local potentials given by Wilmore and Hodgson.[9] While the agreement is found to be reasonably good, it is noted that the measured angular dependence at each energy is slightly more forward peaked than that predicted by these optical model parameters. However, the energy dependence is correct; this is verified by the fact that when the data are expressed in terms of fractional deviation from the optical model values the resulting plot is seen to be energy independent. Thus, optical model predictions can be used to correlate the data from various energies and thereby yield more accurate results than by considering the data at each energy separately. This represents an improvement in the normalization used in our previously reported[1] C, N, and O cross section data at 7.55 and 9.50 MeV, and for this reason the results are revised and included in the following tables and graphs along with the present results.

Because measurements were made for all three elements at each incident neutron energy, the energy spread frequently encompassed regions of structure in the total cross sections for one or more elements. Further, the mean neutron energy was uncertain to about 30 keV. To minimize uncertainities in the final results, an auxiliary measurement was performed; the transmission of each sample was measured under conditions identical to those of the differential scattering measurements, e.g., energy, energy spread, and same sample discs (the center channel of the

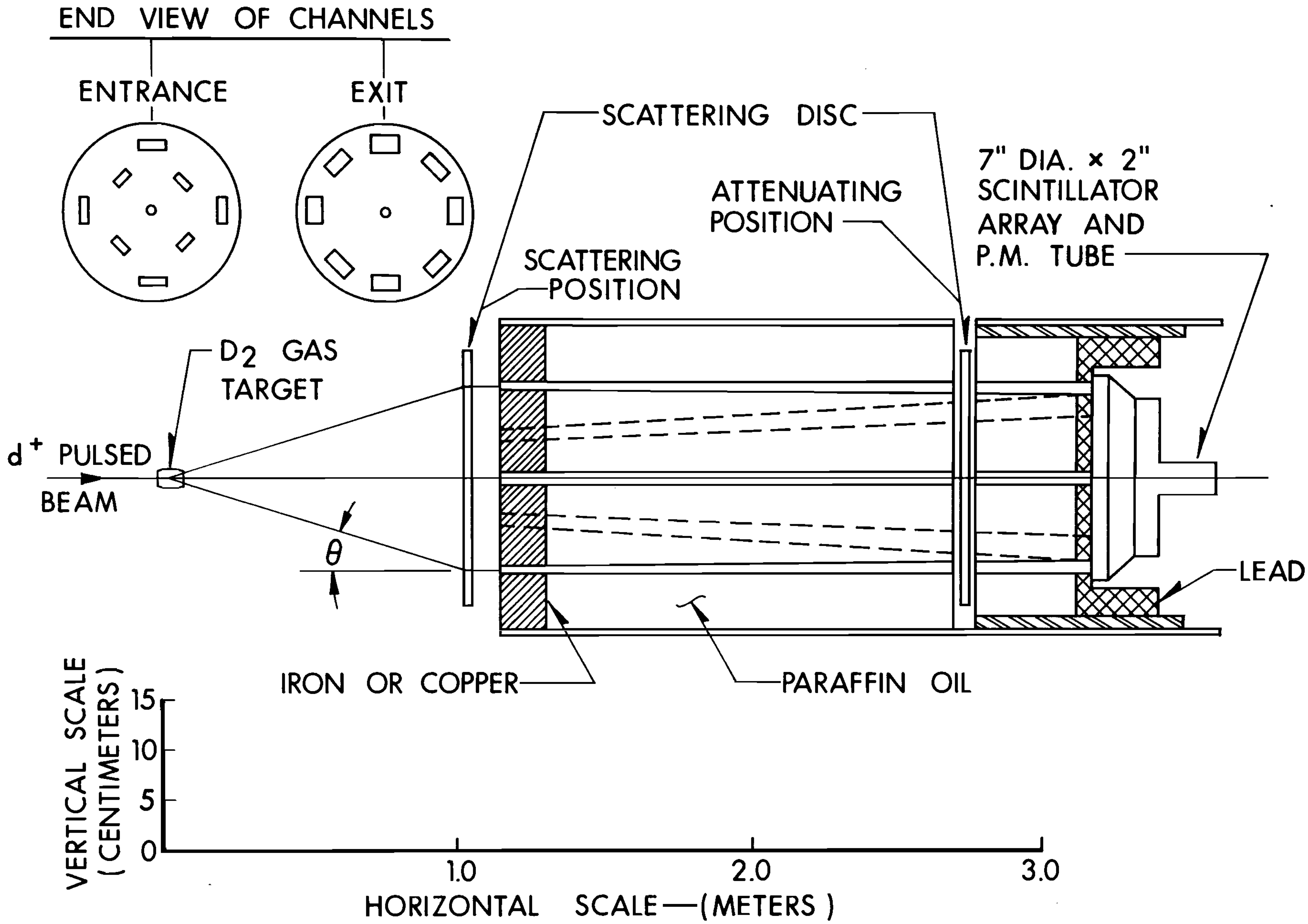

Figure 1. Schematic Diagram of Small-Angle Collimator.

collimator is used for this purpose).

III. RESULTS AND DISCUSSION

The results of measurements of the forward-angle elastic scattering from carbon, nitrogen, and oxygen at 7.40 ± 0.13, 7.55 ± 0.06, 8.00 ± 0.12, 8.55 ± 0.07, 9.00 ± 0.10, and 9.50 ± 0.05 MeV are presented in Tables I-III. The angular resolutions of the measurements were ± 0.7, ± 0.9, ± 1.2, and ± 1.5 degrees for the scattering angles 2.6, 6.6, 10.4, and 14.2 degrees, respectively. The uncertainty in the mean neutron energy is estimated to be 30 keV.

The data are corrected for multiple scattering effects[10] and finite geometry effects are taken into account. The final uncertainty in the oxygen and nitrogen data was magnified by the use of compounds as scattering samples (H_2O and N_2H_4). As an independent check of these data, scattering measurements were also carried out with a CH_2 sample. The results inferred for carbon are in good statistical agreement with that obtained by the use of a graphite sample (or conversely, the correct values for the hydrogen cross section are inferred with the C and CH_2 data). Included in the assigned standard deviations, in addition to the counting statistics, are the uncertainties in the differential cross section for lead (used to normalize the data) and in the transmission of each sample averaged over the energy spread (used to infer the final results from the data).

A. Carbon

Differential cross sections for the scattering of 7.40 to 9.50 MeV neutrons from carbon are shown in Figure 2. In this figure (and in succeeding ones for other elements), the energy-averaged Wick's limit[11] is indicated by an arrow along the vertical axis. Total cross sections used to calculate this value were taken from ENDF/B files, and the square of the cross section was then averaged over the appropriate energy interval. In Table I this limit is given as well as the extrapolated $\sigma(0°)$ as calculated from a least squares fit of the experimental data to the equation $\ln\sigma(\theta) = a - m\,(1-\cos\theta_{c.m.})$, where a and m are constant. The solid curves give the prediction of ENDF/B evaluation 1165 for carbon,[12] appropriately averaged over the experimental energy spread. With the exception of the 8.55 and 9.00 MeV data, which agree well with the evaluation, the measurements are higher than the evaluated curve at all energies. As noted by Perey and Kinney,[13] the carbon evaluation was based on rather meager experimental data. This fact coupled with the strongly resonant nature of fast neutron scattering from carbon suggest that an adequate evaluation of neutron interactions with carbon cannot be expected without several additional experimental measurements.

Our measurements at 7.55 and at 7.40 MeV are in excellent agreement with results ORNL for 7.54 ± 0.06 MeV at large angles. The measured cross

Table I. Cross Sections for Forward-Angle Scattering From Carbon.

	7.40 ± 0.13			7.55 ± 0.06	
$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error
2.9°	668	7	2.8°	690	8
7.4°	641	5	7.2°	604	5
11.3°	583	4	11.7°	596	4
15.4°	518	4	15.4°	534	4
$\sigma(0°)$[a]	678		$\sigma(0°)$	658	
W_L[b]	545		W_L	559	
$\sigma(0°)/W_L$	1.24		$\sigma(0°)/W_L$	1.18	
	8.00 ± 0.12			8.55 ± 0.07	
$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error
2.9°	998	8	2.9°	360	8
7.4°	880	5	7.4°	396	5
11.7°	821	5	11.4°	320	5
15.3°	756	4	15.4°	302	4
$\sigma(0°)$	953		$\sigma(0°)$	393	
W_L	688		W_L	244	
$\sigma(0°)/W_L$	1.39		$\sigma(0°)/W_L$	1.61	
	9.00 ± 0.10			9.50 ± 0.05	
$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr)	% error
2.9°	335	7	2.8°	456	7
7.4°	329	5	7.2°	446	5
11.4°	311	5	11.7°	414	4
15.4°	269	4	15.4°	354	4
$\sigma(0°)$	347		$\sigma(0°)$	475	
W_L	288		W_L	374	
$\sigma(0°)/W_L$	1.20		$\sigma(0°)/W_L$	1.27	

[a] Zero degree differential cross section determined by extrapolation of experimental data.

[b] Minimum value of zero degree cross section determined from Wick's Limit.

Table II. Cross Sections for Forward-Angle Scattering from Nitrogen.

$\theta_{c.m.}$	7.40 ± 0.13 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	7.55 ± 0.06 $\sigma_{c.m.}$ (mb/sr)	% error
2.9°	545	13	2.8°	575	14
7.3°	507	9	7.1°	526	11
11.1°	492	6	11.6°	538	8
15.2°	433	8	15.2°	402	7
$\sigma(0°)$[a]	546		$\sigma(0°)$	609	
W_L[b]	486		W_L	426	
$\sigma(0°)/W_L$	1.12		$\sigma(0°)/W_L$	1.43	

$\theta_{c.m.}$	8.00 ± 0.12 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	8.55 ± 0.07 $\sigma_{c.m.}$ (mb/sr)	% error
2.9°	606	12	2.9°	438	13
7.3°	526	9	7.3°	388	10
11.6°	458	8	11.2°	358	8
15.1°	389	8	15.2°	313	9
$\sigma(0°)$	594		$\sigma(0°)$	427	
W_L	444		W_L	360	
$\sigma(0°)/W_L$	1.34		$\sigma(0°)/W_L$	1.19	

$\theta_{c.m.}$	9.00 ± 0.10 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	9.50 ± 0.05 $\sigma_{c.m.}$ (mb/sr)	% error
2.9°	413	13	2.8°	476	10
7.3°	398	10	7.1°	401	10
11.2°	335	8	11.6°	418	7
15.2°	262	9	15.2°	378	8
$\sigma(0°)$	436		$\sigma(0°)$	455	
W_L	382		W_L	414	
$\sigma(0°)/W_L$	1.14		$\sigma(0°)/W_L$	1.10	

[a] Zero degree differential cross section determined by extrapolation of experimental data.

[b] Minimum value of zero degree cross section determined from Wick's Limit.

Table III. Cross Sections for Forward-Angle Scattering From Oxygen.

$\theta_{c.m.}$	7.40 ± 0.13 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	7.55 ± 0.06 $\sigma_{c.m.}$ (mb/sr)	% error
2.8°	262	22	2.8°	325	16
7.2°	289	14	7.2°	271	14
11.1°	295	11	11.5°	249	14
15.1°	248	11	15.1°	164	14
$\sigma(0°)$ [a]	299		$\sigma(0°)$	331	
W_L [b]	328		W_L	258	
$\sigma(0°)/W_L$	0.91		$\sigma(0°)/W_L$	1.28	

$\theta_{c.m.}$	8.00 ± 0.12 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	8.55 ± 0.07 $\sigma_{c.m.}$ (mb/sr)	% error
2.8°	317	18	2.8°	246	21
7.2°	252	15	7.2°	314	12
11.4°	239	13	11.2°	231	12
14.9°	164	15	15.1°	241	10
$\sigma(0°)$	315		$\sigma(0°)$	290	
W_L	195		W_L	278	
$\sigma(0°)/W_L$	1.62		$\sigma(0°)/W_L$	1.04	

$\theta_{c.m.}$	9.00 ± 0.10 $\sigma_{c.m.}$ (mb/sr)	% error	$\theta_{c.m.}$	9.50 ± 0.05 $\sigma_{c.m.}$ (mb/sr)	% error
2.8°	344	15	2.8°	375	13
7.2°	328	11	7.0°	348	11
11.2°	332	8	11.5°	309	9
15.1°	218	10	15.1°	249	11
$\sigma(0°)$	388		$\sigma(0°)$	384	
W_L	360		W_L	385	
$\sigma(0°)/W_L$	1.08		$\sigma(0°)/W_L$	1.00	

[a] Zero degree differential cross section determined by extrapolation of experimental data.

[b] Minimum value of zero degree cross section determined from Wick's Limit.

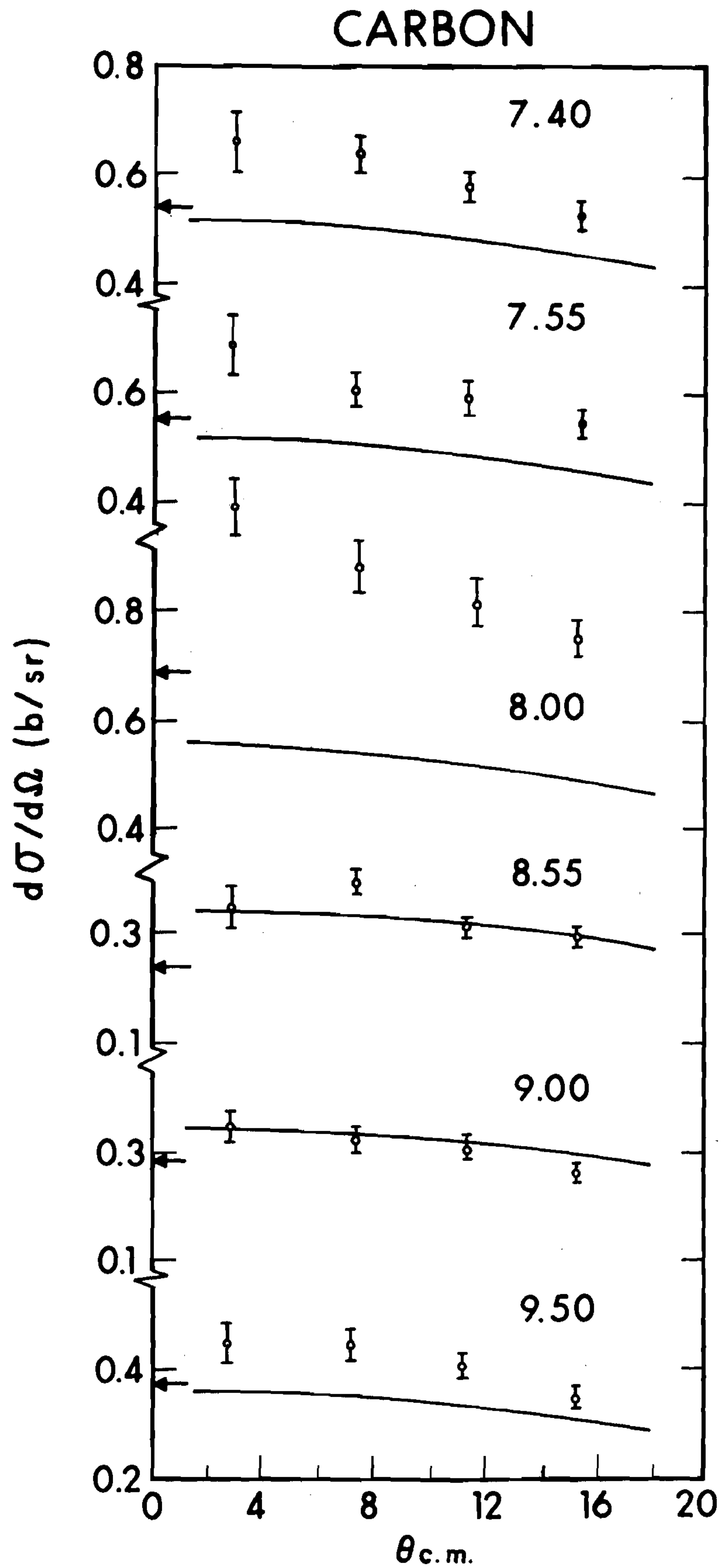

Figure 2. Forward-angle Scattering Cross Sections for Carbon.

sections for 15° scattering at 7.54 and 7.55 MeV agree within 4%. Our 8.55 MeV results for carbon are somewhat lower than the ORNL data at 8.56 MeV; however, in general we obtain results consistent with those of Perey and Kinney (see succeeding discussions).

B. Nitrogen

Our nitrogen results are shown in Figure 3. The solid curves were computed from the recent evaluation of nitrogen data by Young and Foster, ENDF/B MAT 1133.[14] The evaluation is in good agreement with our measurements around 7 and 8 MeV; whereas, the evaluated curve tends to be slightly higher than the measured one for the higher energies. Our results at 7.55 (and at 7.40) join smoothly with the large-angle data of Perey and Kinney.[15]

C. Oxygen

Differential cross sections for forward-angle scattering of 7 to 10 MeV neutrons from oxygen are compared with the Young and Foster evaluation[16] of oxygen data (MAT 1134) in Figure 4. The data are well described by the evaluation except for the 9.50 MeV data which are somewhat lower than the evaluated curve. Our measurements near 15° at 7.55 and 8.55 are consistent with the measurements of Kinney and Perey[17] at 7.54 and 8.56 for approximately the same energy spreads.

IV. SUMMARY

The data presented in this report represent the first direct measurements of neutron cross sections for scattering from light elements at very small angles. These results are of special importance in the case of nitrogen because of the discrepancy in the nitrogen cross sections discussed in Ref. 2. Briefly stated, the elastic scattering cross section obtained by subtracting the measured nonelastic cross sections from the total was approximately 200 mb higher than the elastic cross section obtained by direct measurement.[6]

In their evaluation,[14] Young and Foster assigned the 200 mb of cross section to the elastic scattering cross section. Their choice was influenced in part by our previous measurements[1] of small-angle scattering which indicated that the differential cross section at zero degrees exceeded Wick's limit by about 40% around 7-8 MeV. The data of Bauer, *et al.*[6] would not predict forward cross sections in excess of Wick's limit. A second consideration was that the assignment of the 200 mb to the elastic cross section assumed that only one measurement was in error, that of Bauer *et al.* Conversely, the assignment of this 200 mb contribution to the nonelastic cross section would have implied that several independent measurements of the nonelastic cross section were in error. Our results at small angles and the large-angle data from ORNL

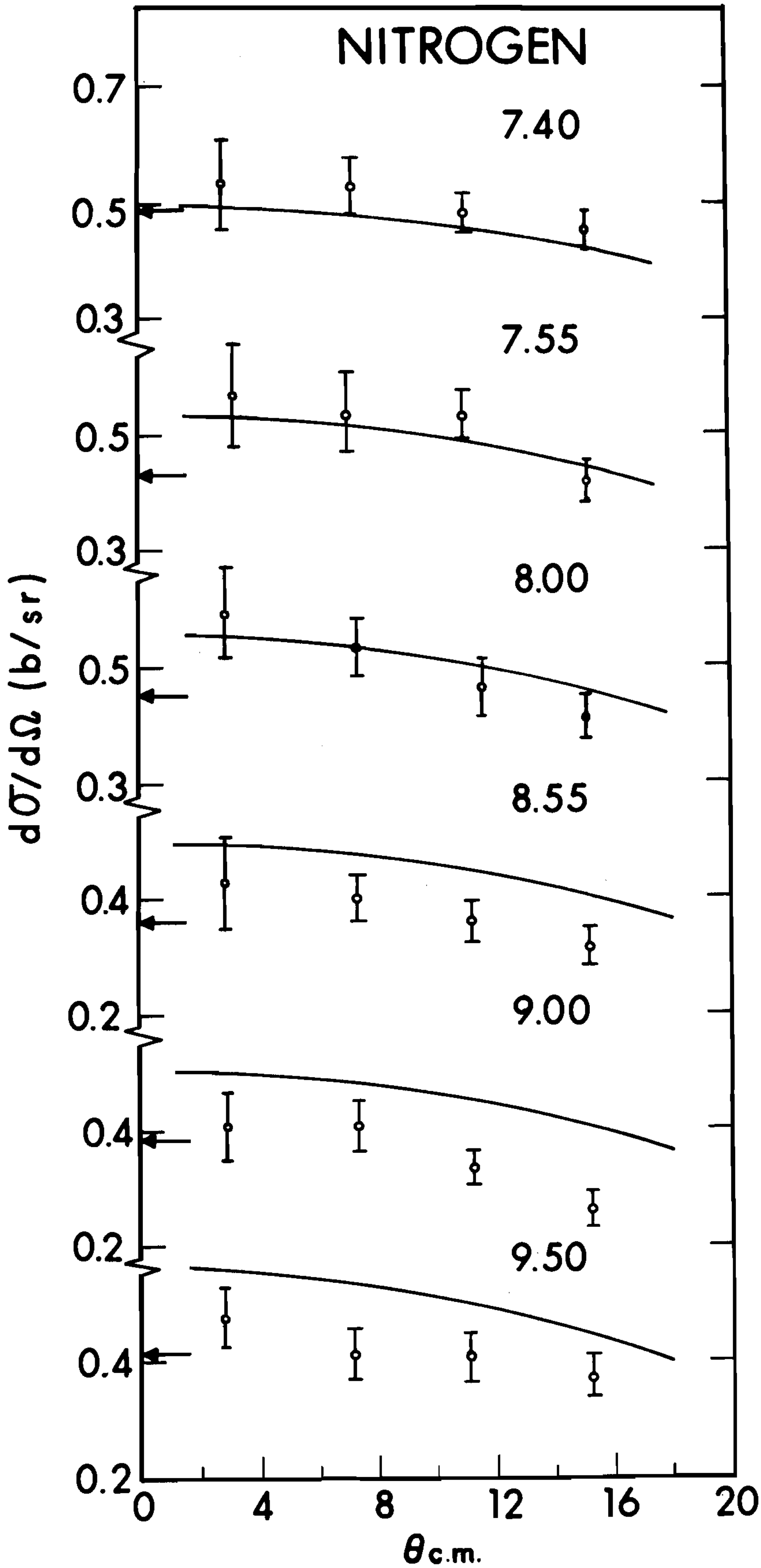

Figure 3. Forward-angle Scattering Cross Sections for Nitrogen.

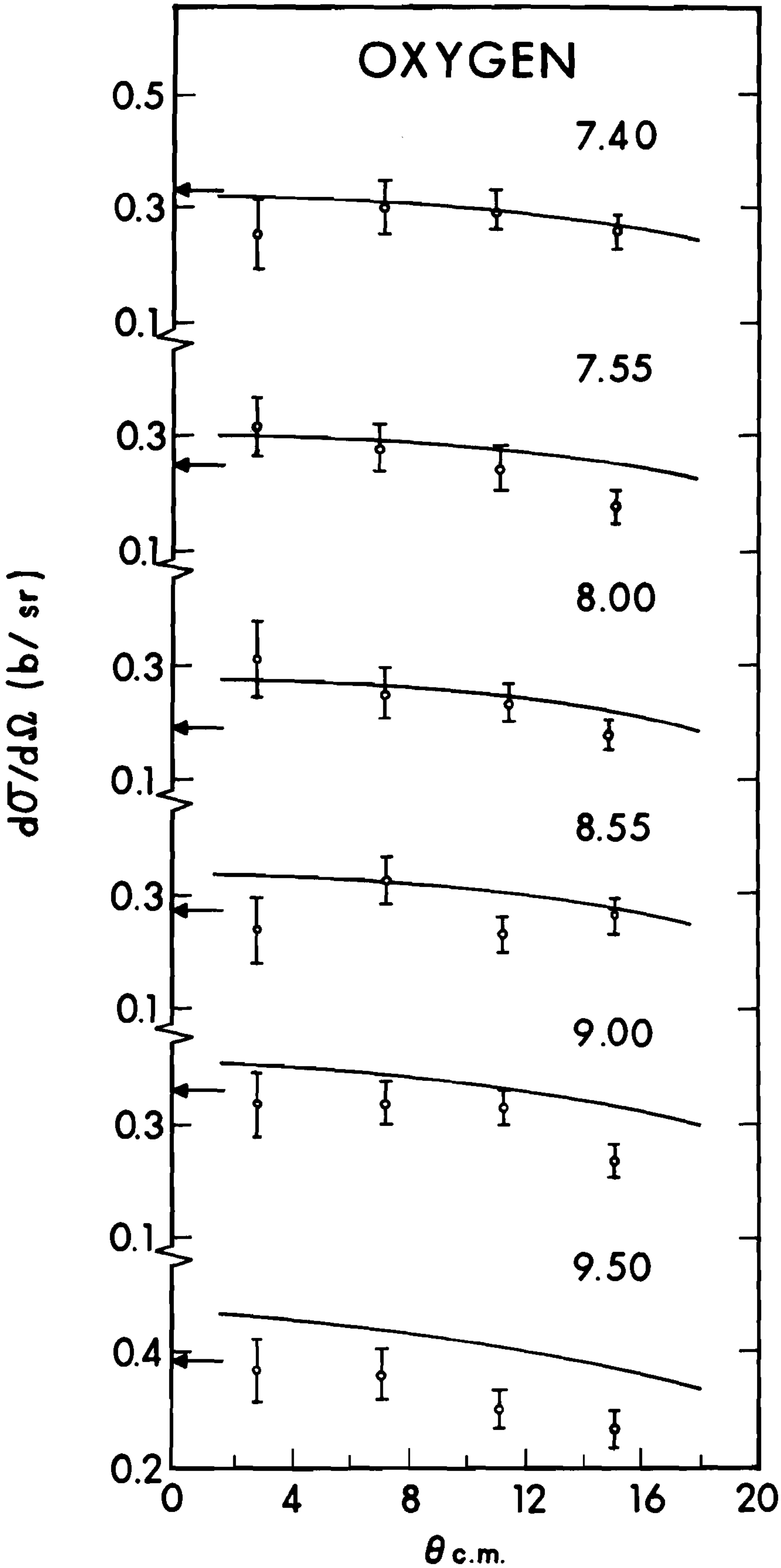

Figure 4. Forward-angle Scattering Cross Sections for Oxygen.

and TNC tend to confirm the choice made by Young and Foster in their evaluation. Furthermore, the results presented here demonstrate that, even with energy resolutions typical of those used in elastic scattering measurements, the zero degree cross sections for light elements appreciably exceed, in some instances, the value given by an energy-averaged Wick's limit. (See Reference 1 for discussion of energy averaging of Wick's inequality.)

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13. ABSTRACT
Absolute differential cross sections for the elastic scattering of 7.40, 7.55, 8.00, 8.55, 9.00, and 9.50 MeV neutrons from carbon, nitrogen, and oxygen in the angular range from 2.5° to 15° have been determined. Measurements were made relative to the scattering from lead by use of a special-purpose collimator. The cross section scale was then established by absolute measurements for lead in a ring geometry experiment. The results for nitrogen are consistent with recent measurements at other laboratories which suggest that the discrepancy in previous nitrogen cross section data around 7-8 MeV neutron energy arose from an underestimate of the elastic scattering cross section. The data presented in this report represent the first direct measurements of neutron scattering cross sections for light elements at very small scattering angles.

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